Effects of storm clustering on beach/dune evolution

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Abstract

Impacts of storm clustering on beach/dune morphodynamics were investigated by applying the state-of-the-art numerical model XBeach to Formby Point (Sefton coast, UK). The adopted storm cluster was established by analysing the observed winter storms from December 2013 to January 2014 using a storm threshold wave height. The first storm that occurred during this period is regarded as exceptionally intense, and the occurrence of such a cluster of events is very unusual. A 1D model was setup for the highly dynamic cross-shore at Formby Point. After initial calibration of the model parameters against available post-storm profile data, the model was used for the simulation of the storm cluster. It was assumed that no beach recovery occurred between adjacent storms due to the very short time intervals between storms. As a result, the final predicted post-storm profile of the previous storm was used as the pre-storm profile of the subsequent storm. The predicted evolution during each storm was influenced by the previous storms in the cluster. Due to the clustering effect, the bed level change is not proportional to the storm power of events within the cluster, as it would be in an individual storm case. Initially, the large storm events interact with the multi-bared foreshore enabling the subsequent weaker storms to influence the upper beach and lower dune system. This results in greater change at the dune toe level also during less severe subsequent storms. It is also shown that the usual water level threshold used to define dune erosion is over predicted by about 1 m for extreme storm conditions. The predicted profile evolution provides useful insights into the morphodynamic processes of beach/dune systems during a storm cluster (using Formby Point as an example), which is very useful for quantifying the clustering effects to develop tools for coastal management.

Key words: *storm cluster*, *dune erosion*, *profile evolution*, *XBeach*, *Sefton coast*, *Formby Point*

1. Introduction

Beach/dune systems which play the role of a natural barrier against coastal inundation are often under threat due to storm-induced erosion (Hanley et al., 2014; Tătu et al., 2014; Harley and Ciavola, 2013; Gómez-Pina et al., 2002; Hanson et al., 2002 and references therein). This poses major concerns for coastal safety and sustainable development in the areas where frontal dune systems are present. Damages to beach/dune systems from storm impacts depend on a number of factors. Large storm events with higher wave heights and extreme water levels cause great damage while storm duration, direction and peak wave period also significantly contribute to the extent of the damage (Karunarathna et al., 2014; Cox and Pirella, 2001). Moreover, occurrence of a series of storms could result in a major impact compared with a single storm with the same characteristics (Coco et al, 2014, Dolan and Davies, 1994). Examples of storm impact on dunes and on coastal systems for series of events can be found in Karunarathna at al. (2014), Ferreira (2005), Callaghan et al. (2008), Vousdoukas et al (2012), Houser (2013), Van Enckevort and Ruessink (2003) and Lee et al. (1998). Karunarathna et al. (2014) showed that clusters of small storms occurred at close intervals can be more damaging than isolated large single storms at Narrabeen Beach Australia. Ferreira (2005) compared erosion due to storm clusters and single events using a long-term wave record from the northwest Portuguese coast and found that storm clusters with small return levels induce average erosion volumes similar to that of a single storm with a larger return period. Callaghan et al. (2008) showed the impact of closely spaced storm events on the erosion volumes using a probabilistic approach. Beach erosion and recovery processes due to consecutive storms were investigated by Vousdoukas et al. (2012). Impacts of foredune morphology on the barrier island response to extreme events at Texas were investigated by Houser (2013). Van Enckevort and Ruessink (2003) showed that the temporal scale of bar position fluctuations is related to the storm sequence. Lee et al. (1998) found that storm groups of close succession can have a large impact on morphology.

An intense storm can cause episodic erosion of a beach/dune system, however, the system generally recovers by onshore sediment transport process (Vousdoukas et al., 2012). The time required for the system to recover to its' pre-storm state is termed the '*recovery period*' (Dissanayake et al., 2015b). If a second storm event which has less erosion potential compared with that of the first, attacks before the recovery period of the first event, more damages are expected to be experienced on beach/dune due to the fact that the system becomes more susceptible to erosion after the first storm event. This is due to reduced wave dissipation across the shoreface following erosion and feature flattening (Dissanayake et al., 2015b). However, the localised impact at the dune toe will depend on the extent to which the frontage has recovered. If it is still set far enough back, the secondary storm may not be able to cause continued retreat as this will be limited by the water elevation relative to the dune toe location enabling the waves to act on the dunes. Therefore, a cluster of storm events tends to worsen storm induced erosion of beach/dune systems compared with that of the single occurrence of a more intense storm (Dissanayake et al., 2015a).

Numerical models which are dedicated to investigate the storm driven evolution, have rapidly advanced over the last years with increased physical processes embedded to predict more accurate and reliable beach/dune evolution (Stive and Wind, 1986; Larson and Kraus, 1989; Roelvink and Stive, 1989; Bosboom et al., 2000; Larson et al., 2004; Roelvink et al., 2009). The XBeach model (Roelvink et al., 2009) is one of the latest developments and an open-source model which is being continually improved by applications in different coastal environments around the world. This model has proven to be capable of predicting storm impacts on morphodynamics of beach/dune systems in numerous case studies (Dissanayake et al., 2014; 2015a,b; Souza et al., 2013; Harley and Ciavola, 2013; Splinter and Palmsten, 2012; Harley et al., 2011;Williams et al., 2011; McCall et al., 2010;   Lindemer et al., 2010). These previous applications motivated us to use XBeach in the present study in order to investigate storm driven beach/dune evolution during an extreme storm cluster, using Formby Point, Liverpool Bay (Sefton coast, UK) as a case study. The hypertidal conditions at this site extend previous research in storm cluster impact to regions where the tidal regime at the time of the storm is also an important factor. The mean spring tidal range is 8.2 m (Brown et al., 2010a), storms that occur during neap or mean tides are therefore unlikely to impact the dune toe unless the surge at high water is large enough to increase water levels to at least similar elevations as those during spring tides (Pye and Blott, 2008). Such storms will however change the beach profile modifying the beach-dune system resilience to later storms. This research therefore enables an assessment of the robustness of typical water level thresholds used to determine likely dune erosion events under extreme wave conditions.

Liverpool Bay and more broadly the Irish Sea has been subjected to numerous research studies investigating the hydrodynamic and morphodynamic characteristics (Brown et al., 2010a,b,c; Wolf et al., 2011; Brown et al., 2012; Brown, 2010, Blott et al., 2006 and many others). Although not all of these results are directly applicable to the Sefton coast, they provide information on the tide and surge interactions, extreme wind and wave events, and also sediment transport and morphological changes which influence the local morphodynamics. Some studies have discussed morphological evolution along the Sefton coast itself (Souza et al., 2013; Esteves et al., 2012; Williams et al., 2011; Esteves et al., 2011; Esteves et al., 2009; Halcrow, 2009; Pye and Neal, 1994; Pye and Blott, 2008) and they have mainly focused on the historical data analysis implying the general patterns of morphological changes. Pye and Neal (1994) analysed the historical shoreline changes from 1845 to 1990 and concluded that centrally the Sefton coast (Formby Point) is eroding while northern and southern parts are accreting. Decadal variation in dune erosion and accretion from 1958 to 2008 was investigated by Pye and Blott (2008) using a series of beach and dune surveys. Only a few studies have focussed on applying numerical models to investigate beach/dune response to storm events (Dissanayake et al., 2014; Souza et al., 2013; Williams et al., 2011). Both Souza et al. (2013) and Williams et al. (2011) have focused on the storm driven dune erosion and potential hinterland flooding on the Sefton coast. They adopted the XBeach numerical model (1D) imposing event-scale wave boundary conditions (i.e. single event) over a few tidal cycles. Dissanayake et al. (2014) used a 2D XBeach model to investigate the Sefton beach/dune response to storm events. This research extends previous studies to look at clusters of storms rather than the previous event based researches.

During the 2013/2014 winter, the UK experienced an exceptional series of storms culminating in catastrophic coastal damages at many locations (e.g. Dawlish, Aberystwyth, see Wadey et al., 2014; Wadey et al., 2015) and widespread, persistent flooding at hinterland areas (e.g. Great Yarmouth, see Wadey et al., 2014). It should be noted that the first storm event that occurred during this period can be regarded as exceptionally severe, and the occurrence of a series of large storms at close intervals was also very unusual (Wadey et al., 2015) and appeared to be more damaging to coastal systems (see UK Met Office report online version, http://www.metoffice.gov.uk/media/pdf/n/i/Recent_Storms_Briefing_Final_07023.pdf).

The objective of the present study is to investigate the morphological changes of a beach/dune system (Formby Point) under the impact of clustered storm events, which occurred in the 2013/2014 winter period. The response of the Formby Point beach/dune system to the clustered storms was investigated through modelling cross-shore profile change and analysing cumulative impact of the storm cluster as opposed to individual storm events. We focus on wave impact over the full cross-shore profile to identify how changes in the lower beach profile (the multi-bared system) influence the vulnerability of the dunes in later storms with higher water elevation. The results found in this study will be very useful for the future management of this highly dynamic beach system as storm clustering during winter months is not unusual in the UK. Also, even though this study is focused on a selected beach, the research findings will be transferable to other sandy hypertidal coastal systems around worldwide.

The structure of this paper is as follows. Section 2 and 3 describe the study area and the cluster of storms occurred in winter 2013/2014. Section 4 describes the modelling approach used to assess the morphodynamic impact of the storm cluster. A discussion of the model results is given in Section 5 while Section 6 provides the conclusions.

2. Study area

The Sefton coast is about 36 km long, convex in shape, and located between two estuaries, the Mersey (to the south) and the Ribble (to the north), in Liverpool Bay (Figure 1a) (Williams et al., 2011). The Sefton coastal system consists of natural beaches/dunes of high recreational value, designated nature conservation sites, engineered beaches protected by seawalls, groynes and revetments and, rubble beaches covered with building material debris and rock armours (Figure 1b). The dunes within the system extend about 4 km inland, reach about 30 m in height at some locations (Esteves et al., 2012) and represent 20% of the UK's dune population (Holden et al., 2011). These dunes form an effective natural coastal flood defence for the local urban areas, high grade agricultural lands and a significant number of conservation areas of national and international interest, which consist of an extremely high biodiversity, forming habitat for a number of rare animals and plants (Edmondson, 2010), e.g., priority habitats in the EU Habitats and Species Directive.

Several coastal management issues have been accelerated due to storm impacts on the Sefton beach/dune system; examples include exposing Nicotine waste that had been buried in the past, and coastal squeeze of land with different uses (conservation, agriculture, leisure and tourism) (Houston, 2010). Success of implementing solutions to these issues depends on the understanding how this complex beach/dune system interacts with coastal storm conditions.

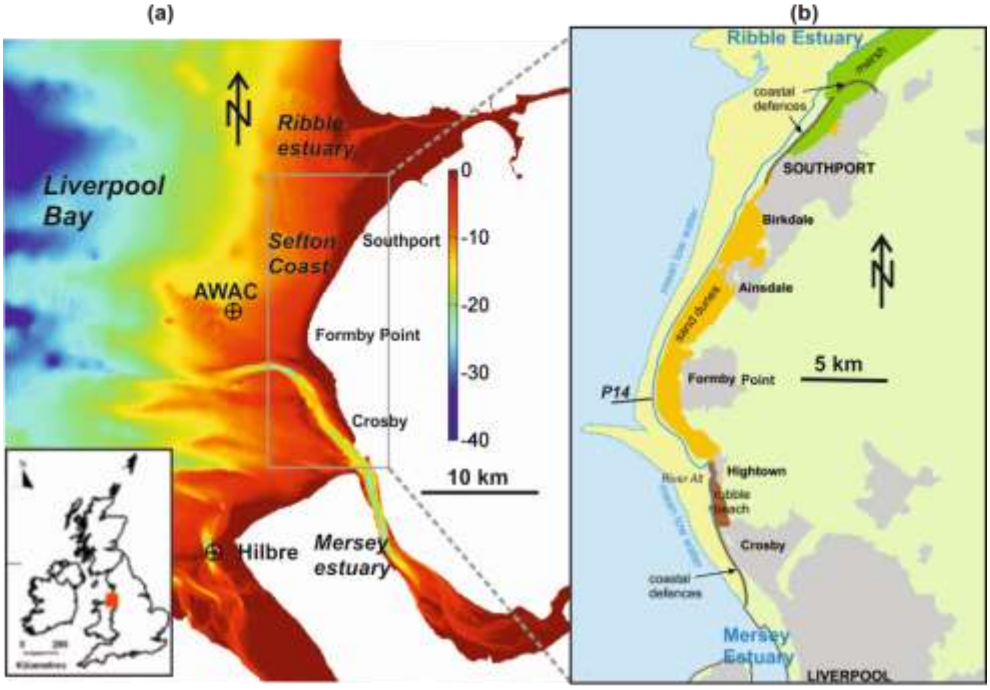

Figure 1 Location of the Sefton coast, Liverpool Bay bathymetry and gauge points; AWAC (wave and water level) and Hilbre (wind) (a), Characteristics of the Sefton coast and selected representative profile P14 (b) (modified from Souza at al., 2013)

The location also has challenging physical conditions, which management plans must consider. Liverpool Bay has an alongshore propagating semi-diurnal hyper-tide with a mean spring tidal range reaching about 8.2 m (Brown et al., 2010a; Palmer, 2010). Brown et al (2010b) simulated an 11-year wave hindcast together with the long-term wave measurements available in the Liverpool Bay and suggest a mean annual significant wave height (H_{m0}) of 0.5 m, with extremes reaching 5.6 m. The mean annual peak wave period (T_p) is 5 s while extremes are about 12 s. Positive surge in the area is often less than 0.5 m however, during stormy conditions, extreme surges of 2.4 m have been recorded along the Sefton coast

(Brown et al., 2010a). The largest surges generally occur during lower water levels (i.e. rising tide) and the maximum surge recorded at high water (i.e. 5.6 m) at the Liverpool tide gauge is about 2 m in 1976 (Brown et al., 2010a). The largest wave conditions are associated with winds from west to north-west where the longest fetch exists (Wolf et al., 2011).

Sediment characteristics of the Sefton coast are determined by inflow of the Mersey and Ribble estuaries, in addition to the net onshore drift due to the tides (Pye and Blott, 2008). Sediment composition in the nearshore is predominantly medium to find sands (Pye et al., 2006). Furthermore, the textural properties around Formby Point show a large content of sand-sized particles from the nearshore area up to the dune system (Holden et al., 2011). The sandy foreshore has a limited grain size variation alongshore with a trend of fining towards the north and south of Formby Point (Pye and Smith, 1988). Median grain size (D_{50}) on this coast varies from about 0.1 mm to 0.3 mm (Millington et al., 2010). Therefore, the average sediment size of 0.2 mm is used in the present study. The inter-tidal area of the Sefton coast is characterised by a series of symmetrical sand ridges which are between 0.5 and 1.0 m high with a wavelength between 150 and 500 m (i.e. multi-bared system), and extend about 3 km seaward with a very mild slope of about 1:100 (Plater and Grenville, 2010).

The primary mechanisms of dune erosion at Sefton are, (i) soaking of the dune toe and (ii) wave undercutting of the wet dune, which can lead to slump of the dune face and dune retreat (Pye and Blott, 2008; Parker, 1975, Plater et al., 2010). The Sefton dune toe is located just above the mean spring high water level. Therefore, dune erosion occurs when extreme storm surge and large waves coincide with the spring-high tide. However, there is a great potential of significant erosion along the coast during storm surges with high wave energy (Halcrow, 2009; Pye and Blott, 2008). Smaller storms erode only a part of the Sefton coast while erosion of the entire dune frontage is possible during the more severe storms, which are larger than a 1 in 10 year event (Pye and Blott, 2008).

Metocean conditions in Liverpool Bay together with the convex shape of the coastline and the beach slope result in differential morphological evolution along the Sefton coast. Some parts experience erosion while others accrete with different rates and trends (Esteves et al., 2012; Pye and Blott, 2008; Pye and Neal, 1994). The area around Formby Point (see Figure 1b) shows relatively high variability in evolution of the beach/dune system. Prior to 1900, this area suffered seaward progradation, however it turned into an eroding system around the beginning of the 20th century (Pye and Neal, 1994; Pye and Smith, 1988; Gresswell, 1953). Local beach/dune erosion at Formby Point delivers sediment to the accreting shorelines both northward and southward (Halcrow, 2009; Pye and Blott, 2008; Pye and Neal, 1994). As a result, Formby Point presently acts as a divergent sediment cell boundary. Esteves et al. (2009) found that the annual dune retreat to the north of Formby Point is about 5 m during the period from 2001 to 2008 and the erosion extends up to the River Alt area (see Figure 1b).

There is a wealth of meteorological and cross-shore profile data covering the entire Sefton coast (Esteves et al., 2009; 2011). One cross-shore profile at Formby Point (P14, Figure 1b), which is the most dynamic area of this coastal system, was selected to model the impacts of the 2013/2014 winter storm-induced beach/dune erosion in this study. The selected profile location is shown in Figure 1b and represents a region of alongshore sediment divergence so a 1D approach is acceptable. This is one of the profiles used in the previous study by Dissanayake et al. (2014) to build on the existing knowledge and monitoring. A number of profile measurements at Formby Point have been undertaken prior to (06th October 2013) and during (09th December 2013) the 2013/2014 winter storm period. The present study uses this information to calibrate the model settings at the selected profile location. The chosen profile (P14) is also adjacent to an Acoustic Waves And Currents (AWAC) instrument (Figure 1a) enabling direct model boundary forcing from observations to reduce error. The AWAC is part of the SMBC shoreline monitoring scheme, thus this model application identifies the event scale impact due to the observed coastal conditions. Such detailed information is often lost due to the bi-annual nature of the beach surveys.

3. Storm event and storm cluster

Storms

Storms are generated due to the atmospheric depressions in weather systems (Weisse et al., 2012). During low pressure periods, sea surface is elevated (by storm surge) and strong wind fields are generated resulting in extreme sea-states. Therefore, the magnitude of both storm wave height and surge level depends on the intensity of a low pressure system. On the other hand, a lower storm wave height generally corresponds to marginal surge levels as the surge levels are intimately related to storms (Weisse and Van Storch, 2009). The Sefton coast experiences storm surges from storms moving in a SW – NE direction from the Atlantic towards Scandinavia and the largest surge (~2.5 m) occurs when the storm track follows a W – NE direction across the British Isles (Brown et al., 2010a). This study further infers that large waves are also generated during the most extreme of these surge events. It should be noted that if a storm event exists more than 6 hours, at least part of the storm coincides with high-tide and thus the combination of high-tide and storm-surge develops extreme water levels leading to increase wave impacts on a beach/dune system. If these conditions occur together with strong wave action, soaking of the dune toe and wave undercutting of the wet dune lead to the most severe erosion of a beach/dune system. Therefore, storm occurrence can be tracked by analysing the observed wave height which consists of larger waves during storms while the higher surge levels occur.

In this study, we classified storms using a threshold storm wave height ($H_{s,threshold}$) which has been estimated by the UK Channel Coastal Observatory (CCO). The site specific $H_{s,threshold}$ are defined around the UK coast by performing statistical significance on long-term storm data and its consistency is evaluated annually (www.channelcoast.org/reports/). These are standard values and are used to identify storms from wave records (Dissanayake et al., 2014; 2015a,b). The established $H_{s,threshold}$ for the Liverpool Bay is 2.5 m. Accordingly, it can be expected that higher storm surges will also occur within the storm period (wave height > $H_{s,threshold}$) as the winds generating high waves will also generate a local surge. It should be clarified that a storm event and dune erosion event can occur for different conditions in hypertidal locations, such as those at Formby Point, while intertidal beach erosion occurs under all storm conditions. For the dunes this discrepancy is due to the variable tidal range. High spring tidal levels enable the background wave action on the dunes to erode the soaked frontage in the absence of a storm (Pye and Blott, 2008), while neap tides limit waves of any severity from reaching the dune toe, thus having reducing or event preventing impact on the dune frontage.

Here we define the storm wave conditions for the Sefton coast that have impact, while acknowledging erosion events may occur under less stormy conditions due to higher tides causing dune soaking. Definitions of storm related parameters in a single event and a cluster are shown in Figure 2. $H_{s,p}$ is the peak storm wave height that occurs during a storm. D is the duration of a storm for which the wave height stays above the threshold value. Repetition time is the duration between initial time points of two consecutive storm events (*RT*). The time interval (*IN*) between storms provides the duration between the last time point of the previous storm and the first time point of the subsequent storm.

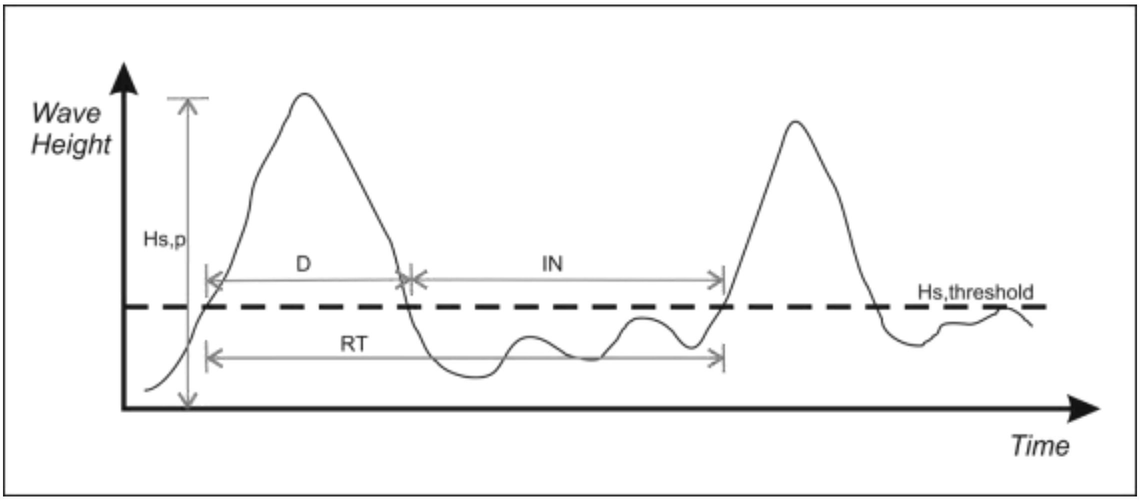

Figure 2 Schematised diagram indicating important storm-related parameters

Accordingly, a storm event is defined based on the storm wave height and the storm duration. When the significant wave height exceeds $H_{s,threshold}$ and $D > 1$ hour, it is considered as a storm event (Callaghan et al., 2008). If $IN > 12$ hours (i.e. the period for a storm event to cross over the British Isles, see Brown et al., 2010a), the second event is treated as an independent storm event, otherwise both events are classified as a single storm. Occurrence of a series of storm events in which 12 hours < *IN* < *recovery period* is classified as a storm cluster. For the Sefton coast the *recovery period* is about one-month according to the analysis of the historical profile measurements. Although this classification does not take into account water level, which is important for dune erosion, it can be used to identify storm events for this research to assess wave driven erosion across both the beach face and dune frontage where water levels allow wave impact. As we select a period of intense storms with variable water levels, we can also assess if the suggested water level threshold for dune erosion (3.9 m ODN, Parker, 1975) is appropriate for use in extreme events when wave setup and run-up modified the water level experienced on the beach. Plater et al. (2010) refer to enhanced dune erosion taking place when the water level exceeds 9.6 m CD. This converts to 5.18 m OD using Parker's (1975) quoted chart datum. Locally, it is therefore suggested a water level of 5.2 m OD is required to cause soaking, which would significantly enhance dune erosion, even when storm waves are not present. However, our focus is on wave impact rather than enhanced erosion due to dune toe soaking.

Storm power index

We aim to assess storm impacts and the applicability of the water level threshold for dune erosion during extreme storm events; we therefore apply the following storm categorisation to identify the storm severity. Storm duration (D) and peak storm wave height ($H_{s,p}$) are of great importance for morphological changes of a beach/dune system during a storm event. Dolan and Davies (1994) and Karunarathna et al (2014) defined 'storm power (S_{pi})' as a function of these two parameters, which can be used as a proxy to determine the strength of a storm:

$$S_{pi} = D \times {H_{s,p}}^2 \qquad (1)$$

It can be seen that *Eq.* (1) overestimates the storm power as a result of using peak storm wave height over the entire duration of the storm (Figure 3a). To overcome this issue, we adopted a slightly different procedure in the present analysis. Initially, the storm wave profile was divided into 'n' sub-segments of which each has a duration ΔD and storm wave height ΔH_i (Figure 3b). Then, the storm power index was estimated by:

$$S_{pi} = \sum_{i=1}^{n} (\Delta D \times {\Delta H_i}^2) \qquad (2)$$

The variability in wave height during a storm is then well captured (i.e. a single peak event, multi-peak event or sustained peak storm wave height for a long period, etc.). Therefore, this power index given in *Eq.* (2) provides a better representation of the strength of a storm.

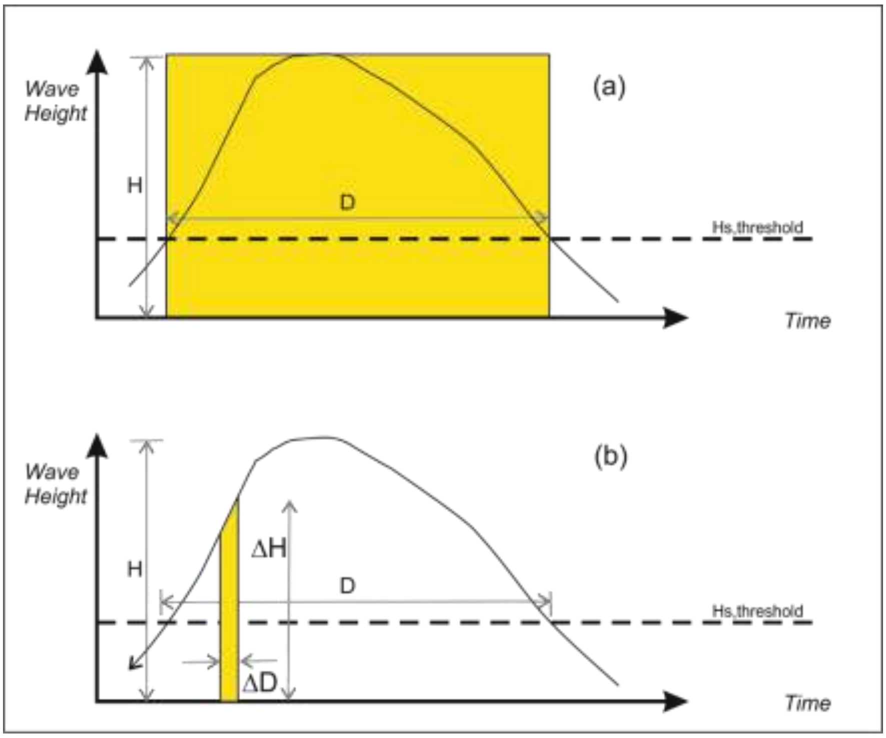

Figure 3 Schematic diagram showing estimation of storm power index using Eq.1 (a) and Eq. 2 (b)

Winter storms from December 2013 to January 2014

Our study used the sequence of closely spaced storms, which impacted the west coast of UK during December 2013 and January 2014. Metocean conditions during these storms have been captured at regular monitoring locations in the Liverpool Bay (Figure 4). Tidal elevation and resulting surge levels have been recorded by the AWAC (see location in Figure 1a). Water elevation (blue-line) and surge levels (red-line) are shown in Figure 4a together with the threshold water level (3.9 m (black-dash-line)) which is suggested for dune erosion by Parker (1975) while significantly enhanced dune erosion occurs exceeding 5.2 m (corresponding value to 9.6 m CD in Plater et al., 2010). The maximum water level is about

5.7 m ODN during this period. It is evident that the higher surge elevations more frequently occurred during neap-tide rather than spring-tide. However there are still three extreme storms with high waters during the period where the total water elevation due to tides and surge exceeds the threshold limit for dune erosion (see Table 1).

Wave characteristics at the AWAC are shown in Figure 4b together with the CCO defined threshold wave height of 2.5 m (black-dash-line). Wave height (blue-line) shows several peaks exceeding the storm threshold limit and these belong to the selected storm events (D1 – D3 and J1 – J4). Wave directions (green-square) indicate that the dominant direction is from northwest (NW). By selecting nearshore storm events we are also able to assess how the nature of the waves is transformed at the coast before impacting on the beach/dune system.

Wind information are based on the Hilbre weather station (Hilbre in Figure 1a) at which wind data are measured at 10 m above the ground level. Dominant wind direction approaching the Sefton coast is from the North-West quadrant (see Figure 4c) during this period. The maximum wind speed during the December – January period is about 24 m/s.

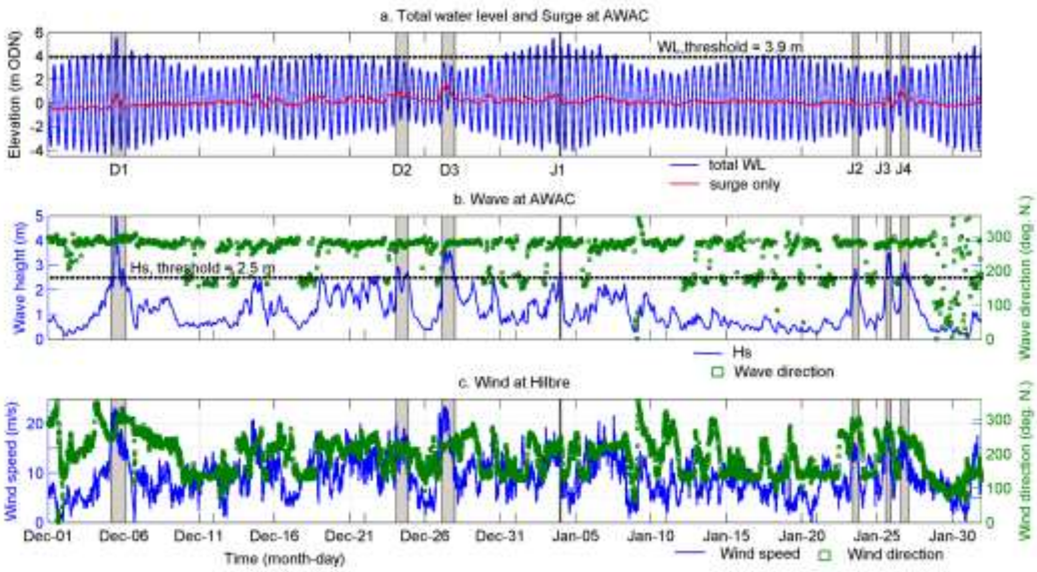

Figure 4 Metocean conditions during December 2013 – January 2014 storm period; Total water level and Surge at the AWAC location with the threshold level (3.9 m) for dune erosion (a), Wave characteristics at the AWAC location with the threshold storm wave height (2.5 m) (b) and Wind characteristics at the Hilbre location. See Figure 1a for the locations. The grey-bars indicate the selected storm events (December: D1, D2, D3 and January: J1, J2, J3, J4)

Coastal storm events influencing the Sefton beach/dune system during December 2013 and January 2014 were extracted using the definition described in Figure 2 and that resulted in three storm events in December 2013 (see D1, D2 and D3 in Figure 4) and four storm events in January 2014 (J1, J2, J3 and J4 in Figure 4). Variation of water elevation (WL: tide+surge), surge and wave height (H_s) at the AWAC location during each storm event is shown in Figure 5 together with thresholds wave height ($H_{s,threshold}$) and threshold water level for dune erosion (3.9 m ODN; Parker, 1975). The maximum wave height in all storm events coincides with the period of high-water implying that the selected storms enable high impact on the beach/dune morphodynamics. It should be noted that the threshold water level for dune erosion is exceeded/reached during three events (D1, D2, and J1) while other events (D3, J2, J3 and J4) show relatively low high water levels.

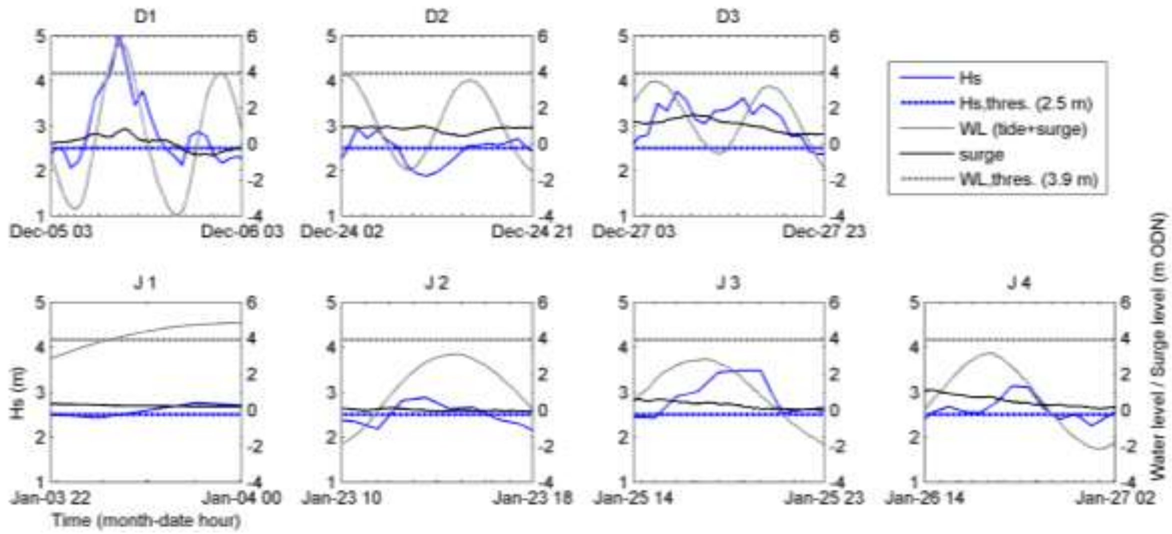

Figure 5 Variation of wave height (H_s: blue-line), storm threshold wave height ($H_{s,threshold}$: blue-dash-line), water level (WL, Tide+Surge: grey-line), Surge (black-line) and threshold water level for dune

erosion(grey-dash-line) at the AWAC (see location in Figure 1a) during the selected isolated storms in December 2013 (D1, D2 and D3) and January 2014 (J1, J2, J3 and J4)

D1: This event occurred during spring-tide, extended from the 05th to 06th December spanning about a one-day period and has the largest storm power of 266 m^2hr. The peak storm wave height (5 m) coincides with the highest water level (5.6 m ODN) which resulted from spring high tide and the highest surge (max. ~ 0.8 m ODN) during the storm. Therefore, large impacts on the beach/dune system are expected within D1 as the dune toe level at Formby Point (P14, see Figure 1b and later Figure 6) is located at around 5 m ODN (Pye and Blott, 2008).

D2: The second storm occurred with a storm power of 110 m^2hr in the intermediate period between spring- and neap-tide spanning about 19 hours on the 24th December. In the beginning of this event, wave heights exceeded the threshold storm wave height (2.5 m) and reached a maximum of 3.0 m at the highest water level of 3.9 m ODN, then fell below the threshold before rising again up to 2.7 m. Since the wave heights exceed the threshold value at the beginning and at the end of this period and are less than 12 hours apart (i.e. IN < 12 hours), the entire period was considered to be a single storm event. Surge levels remained relatively stable (~0.9 m) within this period. Erosion could occur at the dune toe due to the combination of high water levels and wave setup and wave run-up increasing the water level on the beach. Since this is the second event any slumped material during the first when considered in a cluster scenario could be at risk of erosion removing it as a source that could aid dune recovery.

D3: The last storm event in December was on the 27th during neap-tide and lasted for about 20 hours with a storm power of 185 m^2hr. Wave heights during this storm exceeded the storm threshold for the entire storm period and show a double-peak of which the maximum reached 3.8 m at water level of 2.4 m ODN. The highest water level (3.5 m ODN) occurred at the outset of this storm and that corresponds to a wave height of 3.5 m. The surge levels reached up to 1.6 m ODN. Though the water level is lower than that of the dune toe, strong morphological changes can be expected on the upper beach area in this event due to the large waves.

J1: This storm approached the Sefton coast on the 3rd January during high water spring-tide and spanned 2.5 hours with the smallest storm power (15 m^2hr) in the series. Water levels increased from 2.9 to 4.8 m ODN and were close to the dune level for more than 2 hours during this event while the surge level remained almost stable at 0.3 m ODN. Wave height also generally increased in this period and the maximum conditions reached 2.8 m at 4.7 m ODN of water level. There is a potential for impact on the dune frontage (i.e. water level > 3.9 m) though the wave height is lower compared with the previous events.

J2: The next storm with a storm power of 52 m^2hr occurred on the 23rd January and lasted 8 hours. A large part of the storm coincided with the high water during the intermediate tide between spring and neap, which has a maximum water level of 3.1 m ODN. The maximum surge reached about 0.1 m ODN and remained fairly stable. Wave heights decreased below the threshold in the beginning and the end of the event and reached a maximum of 2.9 m at a water level of 2.7 m ODN. This event cannot reach the dune toe level. However, it is expected large changes in the nearshore multi-bared system and on the upper beach area will have occurred changing the wave dissipation for subsequent events.

J3: After about two days from the previous storm, on the 25th January, this storm occurred for a period of 9 hours and has a storm power of 83 m^2hr. The majority of the event overlapped the high water during the neap-tide (max. ~ 2.8 m ODN). The highest surge of 0.6 m ODN occurred at the beginning of the event before decreasing to 0.01 m ODN within the storm period. The maximum wave height of 3.5 m remained stable for about 2 hours while water level decreased from 2.6 to 0.8 m ODN. This event also could result in strong morphological changes up to the upper beach area.

J4: The longest storm duration in January was recorded in this event which lasted for 12.5 hours on the 26th with a storm power of 82 m^2hr. A large part of the storm approached during high water in the neap-tide with a maximum of 3.2 m ODN. As in the previous event (J3), the surge level gradually decreased from 1.1 to 0.2 m ODN during the storm. The storm peak wave height of 3.1 m was stable for about 1 hour when the water level decreased from 2.5 to 1.5 m ODN. It is expected, morphological changes will occur up to the upper beach area as the water level is not sufficient to reach dunes.

The details of each storm event are summarized in Table 1. Accordingly, it is evident that D1 event had the longest storm duration (24.5 hours) and the highest storm peak wave height (5.0 m) occurring at water level of 5.6 m ODN and strong NW wind (20 m/s). The D2 event occurred 9.6 days after D1 while D3 and J3 have shorter storm intervals (i.e. 2.2 and 1.8 days respectively). The longest storm interval of 19.3 days was found between J1 to J2 and the shortest interval of 0.6 days was found between J3 and J4. It is thought that dune erosion occurs for events with water elevations exceeding 3.9 m ODN (Parker, 1975). Since our events include conditions that exceed and sit below this threshold (Table 1), we can test this critical level for extreme storm wave events for dunes that at the time of storm impact are well setback from this threshold in their winter position (of ~ 5 m ODN).

	Characteristics at storm peak Hs						Maximum water level (m ODN)	D (hours)	IN (days)	Storm power (m^2hr)
Storm event	Hs (m)	Tp (s)	Direction (deg.N)	Wind speed (m/s)	Wind direction (dir. N)	Water level (m ODN)				
D1	5.0	8.7	280	20	295	5.6	5.6	24.5	-	266
D2	3.0	7.2	272	14	191	3.8	3.9	19.5	9.6	110
D3	3.8	8.0	270	18	225	2.4	3.5	20.0	2.2	185
J1	2.8	6.4	264	15	233	4.7	4.8	2.5	4.9	15
J2	2.9	7.1	284	15	289	2.7	3.1	8.0	19.3	52
J3	3.5	8.6	290	17	281	2.6	2.8	9.0	1.8	83
J4	3.1	8.1	283	14	252	2.5	3.2	12.5	0.6	82

Table 1 Selected storm events for December (D1, D2, D3) and January (J1, J2, J3, J4) and their characteristics when the peak storm wave height occurs

Analysis of the cross-shore profile changes along the Sefton coast from 2001 to 2009 indicates that the dune toe level at Formby Point continuously retreats and only partial recovery occurs after severe storm events (Esteves et al., 2012). Furthermore, it is shown that only a few meters of erosion/accretion occurs annually around Formby Point (Pye and Blott, 2008). In the first event of the selected 2013/2014 winter storm period (D1), severe erosion occurred leading to more than 4 m retreat at the dune toe level and this has not been yet recovered even after about a one-year period (Dissanayake et al., 2015a). This indicates that post storm recovery of the Sefton coast takes place at considerably slow rates and that the recovery period may be longer than a month as suggested initially. The maximum interval between the selected storm events is about 19 days (< *recovery period*) and therefore the sequence of the above storms can be considered as a single cluster herein.

It should be noted that, in some events, the water level was not high enough to reach the dune toe. However, these events together with higher waves will enable strong morphological changes from the nearshore multi-bared system up to the upper beach area. Wave setup and run-up will also enable the water level on the beach to exceed that in coastal waters, potentially enabling impact on the dunes if high enough. Moreover, occurrence of these lower water level events in a cluster could lead to the subsequent event more easily reaching the beach/dune systems as the previous events flatten the nearshore bed topography and reduce the wave dissipation.

4. Modelling approach

The XBeach morphological model (Roelvink et al., 2009) is used to investigate the beach/dune system evolution under the cluster of storms described in Section 3.0. It has been demonstrated that this model has high predictive capacity of dune evolution under storm attack in a number of case studies (Roelvink et al., 2010; McCall et al., 2010; Souza et al., 2013; Pender and Karunarathna, 2013; Harley and Ciavola, 2013; Splinter and Palmsten, 2012; Harley et al., 2011; Williams et al., 2011; Lindemer et al., 2010). In this study, we simulated cross-shore profile evolution (i.e. a 1D domain) to estimate the storm cluster impacts on the Formby beach/dune system. Initially, a model calibration was carried out using measured pre- and post-storm profiles of the storm event D1. Then, the calibrated model settings were used to simulate storm impacts of the selected storm cluster (D1, D2, D3, J1, J2, J3 and J4). It is emphasized that the predicted final profile of the previous storm was used as the initial state for the subsequent storm erosion simulation. Such an approach optimised the computational time considering the fact that the recovery occurred between adjacent storm events is negligible.

1D model domain

Formby Point is characterised as a divergent sediment cell which supplies locally eroded sediment towards the south and north (Esteves et al., 2012; Halcrow, 2009). Therefore, the alongshore transport at Formby Point is herein assumed to be minimal. This allows safe selection of our 1D domain at P14 (see location in Figure 1b). At P14, the nearshore beach/dune profile (from the dunes to -2 m ODN depth) was defined by the pre-storm measured profile data provided by the SMBC. Profile depths from -2 m to -8 m ODN were estimated using the historical monitored data. A constant slope of 1:500 was adopted from -8 m to -20 m ODN depth, based on the averaged offshore sea bed (Brown, 2010) in order to extend the computational domain to accurately generate offshore boundary conditions (Dissanayake et al., 2014). The offshore grid resolution was selected as 10 m while a higher grid resolution (~ 2 m) was used across the beach/dune area.

Initial bed topography of this cross-shore profile is shown in Figure 6. The zoomed-out view shows the topography within the first 2 km from dunes. The cross-shore length of the domain is 14 km and the multi-bared patterns occupy about 2 km from 12 km to 14 km (i.e. depth ~ -6 m ODN, see subplot).

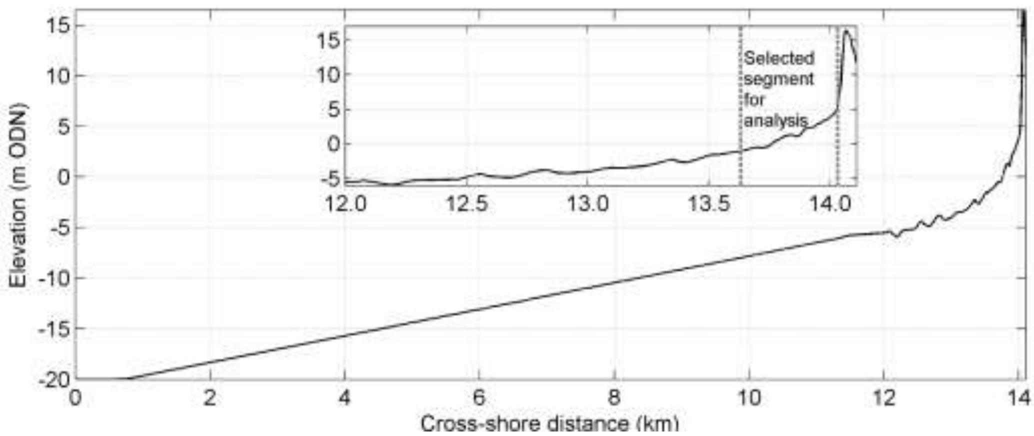

Figure 6 Constructed 1D model domain for XBeach at location P14 (see Figure 1). The subplot shows the selected segment for the analysis.

Boundary forcings

The model runs were forced by tide, wave and wind boundaries. Observed total water elevation and wave data at the AWAC, and wind data at Hilbre (see locations Figure 1a) were used to force the model simulations. Initially, separate time series of boundary forcings were established using the initial and final time of each selected storm event (i.e. December (D1, D2 and D3) and January (J1, J2, J3 and J4)).

Model simulations

Initial model runs were carried out using the measured profile information during the storm D1 to calibrate the model settings in the first series of simulations (Series 1 in Table 2).

Thereafter, modelling of morphodynamic impacts of storm clustering on the Formby Point beach/dune system was carried out in two series of simulations. In the second series (Series 2), profile evolution from the storm cluster was simulated taking the post-storm beach profile from the previous storm as the initial profile for the subsequent storm. In this approach, it is expected to observe the cumulative effect of morphological change from the storm cluster. In the third series (*Series 3*), model runs were carried out taking the same initial bed topography (the pre-storm profile of D1) for all storms. This represents the assumption that each event impacts a fully recovered system from any previous event. Comparison of morphological changes from these two series of model runs provides better understanding of the storm clustering impact on the beach/dune evolution.

Simulation	Description
Series 1	Calibrate the model settings by comparing pre- and post-storm profiles during the D1 event
Series 2	Investigate cumulative effect of storm clustering on the profile evolution. In this case the post-storm profile after the previous storm was taken as the initial profile of the subsequent storm erosion
Series 3	Apply the same initial profile for each storm event (i.e. all storms impact the same system representative of a fully recovered state)

Table 2 Model simulations undertaken in this study

5. Results and Discussion

5.1 Model calibration

The 1D model setup was calibrated for the D1 storm in which pre- and post-storm profiles at P14 are measured by the SMBC. Morphodynamic predictions of XBeach are sensitive to a number of model parameters (Pender and Karunarathna, 2013; McCall et al., 2010; Lindemer et al., 2010). However, only two parameters which are found to give the highest contribution to morphological changes of beach/dune systems are used in the calibration. These are: 1) the calibration factor for time averaged flows due to wave skewness (*facSk*) and 2) the calibration factor for time averaged flows due to wave asymmetry (*facAs*). The sediment transport rate in XBeach is estimated using a representative velocity which is a function of flow velocity and advection velocity from wave skewness and wave asymmetry (Roelvink et al., 2009). Therefore, applying different values to the calibration factors of skewness (*facSk*) and asymmetry (*facAs*), the magnitude and direction of net sediment transport and in turn the morphodynamic predictions are changed. These coefficients generally vary from 0 to 0.8 according to the boundary forcings and topographic conditions of the study area (McCall et al., 2010).

A series of simulations were undertaken by changing the values of these two parameters systematically around the default settings. Model runs spanned the period of the D1 storm event and were forced by the corresponding tide, wave and wind variations.

The optimised values for facSk and facAs were selected by comparing the predicted final profile with that of the measured post-storm profile of D1, using two statistical parameters; Root-Mean-Square-Error (RMSE) and Brier-Skill-Score (BSS, see Van Rijn et al., 2003). The lower the RMSE and the higher the BSS the better the model performance is. Resulting values of the statistical parameters are shown in Table 3 together with the implemented values for facSk and facAs.

facSk	*facAs*	RMSE	BSS
0	0	0.11	0.63
0.1	0.2	0.13	0.51
0.1	0.4	0.15	0.34
0.1	0.6	0.16	0.21
0.1	0.8	0.18	0.09
0.2	0.2	0.14	0.45
0.4	0.2	0.14	0.39

Table 3 Statistical comparison of the calibrated profile evolution using different *facSk* and *facAs* during the storm event D1

The lowest RMSE value (0.11) and the highest BSS (0.63: classified as *Good* in Van Rijn et al., 2003) at P14 are found with *fasSk*=0 and *facAs*=0. RMSE generally increases and BSS decreases as the *facAs* increases. It appears that *facAs* is influential on the bed evolution than *fasSk* , implying that wave skewness has relatively low contribution to the sediment transport than that of wave asymmetry at this site.

The predicted post-storm profile after applying the optimised model parameter settings (*facSk* and *facAs*) is shown in Figure 7 together with the measured pre- and post-storm profiles during D1. It should be noted that this section of the profile was selected according to the availability of the measured storm profiles. By comparing the measured profiles, it is evident that the initial multi-bared pattern is completely flattened during the storm. This feature is sufficiently reproduced by the model (see black-line and black-cross-line) as found with the statistical values. A lower agreement is found around the dune toe level (~5.0 m ODN) and below MSL. Around the dune toe, the model has underestimated the slumping of upper dunes compared with the observation leading to slight erosion on the initial profile. Below MSL, the model resulted in relatively low accretion. These discrepancies are mainly attributed to the fact that there is a time difference between measured pre-storm profile (on the 6th October 2013) and the storm occurrence (on the 5th December 2013) in D1 so the actual pre-storm profile is likely to be slightly different influencing the system response.

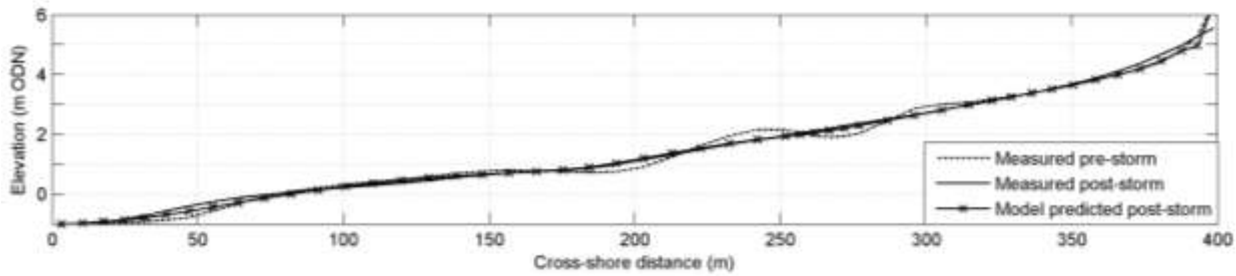

Figure 7 Comparison of measured and predicted cross-shore profile evolution at Formby Point (P14) during the storm event D1

The modelled profile evolution of the calibration run at P14 showed a reasonable agreement with the measured data and is hereon adopted to investigate the impacts of the 2013/2014 storm cluster.

5.2 Bed evolution during the winter 2013/2014 storms

The calibrated profile model discussed in Section 5.1 was used to simulate profile evolution during the winter 2013/2014 storm cluster. As mentioned earlier, the first set of simulations was undertaken applying the post-storm profile from the previous storm as the initial profile for the proceeding storm. In the second set of simulations the same initial profile was taken as the pre-storm profile for all storms to impose full beach recovery in between each storm event in the cluster.

Cross-shore profile change

The final predicted profiles during storms within the cluster and recovery applications are shown in Figure 8. It should be noted that the evolution in D1 is not given as the predicted profiles are the same in both applications. In the other storm events, marked differences in the final profile are found depending if the storm impacts the already-damaged beach/dune system (cluster, Series 2, Table 2) or the same initial bed topography (recovery, Series 3, Table 2). All the storms in the cluster (Series 2) resulted in smooth and completely flattened multi-bared profile compared with that of the initial state. In the recovery (Series 3) results, the impact on the multi-bared system seems dependent on storm power (i.e. storm power in D3 (185 m2hr) > D2 (110 m2hr) and D3 has greater ability to flatten the system). Storm impacts in the recovery simulations exceed the dune toe level (~5.0 m ODN) during the D1and J1 storms only due to high water level in these two events (i.e. 5.6 and 4.8 m ODN respectively). The threshold level for dune erosion (3.9 m ODN, Parker, 1975) is also exceeded during D2. In the majority of simulations the recovery profile indicates erosion at the ridges and accretion at the runnels though this becomes more prominent in the cluster simulation. In the recovery application, the lowest severity event (J1: 15 m2hr) of these storms, the initial pre-storm profile was maintained over the lower beach, thus indicating negligible change on the multi-bared pattern, although it impacted the dune toe level as the maximum water level reached 4.8 m during this event. The fact the water level of this event allows impact on the dunes, with minimal influence on the multi-bared system, suggests duration of wave action is more important than the wave height when considering erosion events of the multi-bared system, but water level is more important than wave power for dune erosion. Storm impacts at the multi-bared increase from J2 (storm power: 50 m2hr) to J3 (83 m2hr) in the recovery as the storm power increases in these two events. However, the system response is not equivalent to that in the cluster. In the last event (J4: 80 m2hr) the resulting erosion and accretion patterns are more or less similar to J3 in the recovery simulation implying similar storm impacts within these two events though there is a slight difference in the storm severity. The profiles presented clearly show the impact of the storms in isolation, while the impact of the each storm within the cluster is hard to define as the pre-storm profile is not presented, so the cumulative impact of previous storms is not seen. However, focusing on the dune toe, the impact of the lowest powered storm (J1) is seen as this modifies the dune frontage imposing a different initial dune profile in all subsequent storms in the cluster simulations. Unlike D1, J1 is low power so the eroded material from the dunes remains on the upper beach – dune interface slightly modifying the availability of sediment to be eroded in the later storms.

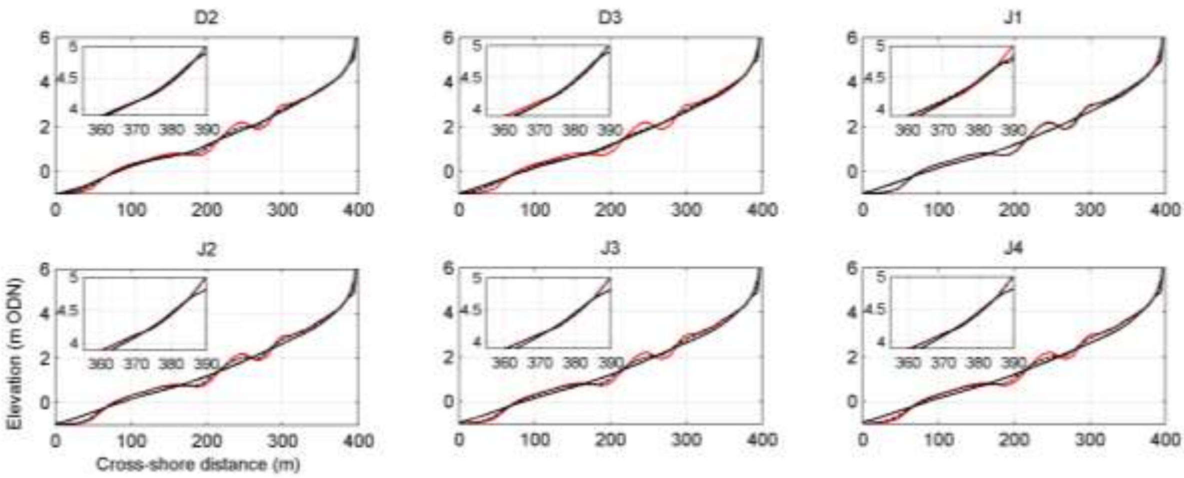

Figure 8 Final predicted cross-shore profile (P14) within Cluster (black-line) and Recovery (dash-line) applications during storm events: D2, D3, J1, J2, J3 and J4. Initial profile indicates by red-line. The zoomed-out view shows evolution between 3.9 and 5.0 m ODN.

The profile evolution provides a qualitative impression of the clustering and recovery effects on the storm impacts at Formby Point. We further analyse the bed level change in each storm event within the cluster and the recovery applications to obtain the quantitative impression. The event driven change in bed-level across the profile for both simulation series is compared in Figure 9 (black '+' below and red '+' above the 3.9 m ODN). Bed level changes are mainly found in the 1st and the 3rd quadrants indicating that both applications resulted in the similar (positive or negative) trend in evolution. As mentioned earlier, D1 resulted in the same impacts in both cases as it is the initial storm of the cluster. The bed level changes therefore line of a straight line mainly populating the range -0.1 to 0.1 m, while the maximum exceeds -0.4 m. For the other events the spread of points in the *y* direction on the plots is generally larger than that in *x*. This implies the bed level change within a storm event is higher when a storm occurs on the fully recovered profile compared with that when it impacts an already-damaged profile. This is expected due to the fact that storms in the recovery series interact with the initial multi-bared pattern (see black '+'). Also, it should be noted that the majority of bed changes are small (i.e. points are around zero) with large changes occurring only at some locations (i.e. at multi-bared features, see Figure 8). In D2, D3 and J1 there is some horizontal variability as well. This suggests that after 4 storms (from D1to J1) the beach/dune profile has reached a state where any continued impact has minimal effect. The difference between the cluster simulations and recovery simulation is confined to locations where the cluster simulations have near 0 bed level change, suggesting the cluster of storms are no longer having much impact on the evolved system profile. Relatively large impacts on the dunes (see red '+') are found in D1, D3 and J1. The fact, there is dune impact in D3 and J1but not D2, suggests that low waves require water levels to exceed 3.9 m ODN to have an impact, but for larger waves the water level can be lower than 3.9 m 0DN. For J1 there are 4 points that experience horizontal spread and represent dune impact, 2 of these experience zero bed level change in the recovery simulation and erosion in the cluster simulation. This shows how the 3 initial large events have made some points on the dune system more susceptible to erosion under this weak event of high water elevation. In D2, the maximum erosion and accretion in the recovery is about 0.25 m and the corresponding value in the cluster is about 0.03 m. D3 resulted in a slightly higher value in the recovery (-0.32 m) and that corresponds to -0.01 m in the cluster. The maximum bed change within the January storms: J1, J2, J3 and J4 ranges from -0.23 to 0.22 in the recovery. In fact, their corresponding values in the cluster are about -/+0.02. Therefore, the storm impact in the cluster is one order of magnitude lower than that of the recovery storm simulations. It is emphasized that bed change was herein compared considering maximum values occurred in the recovery. However, there are some locations on the profile that experienced relatively higher change in the cluster than in the recovery.

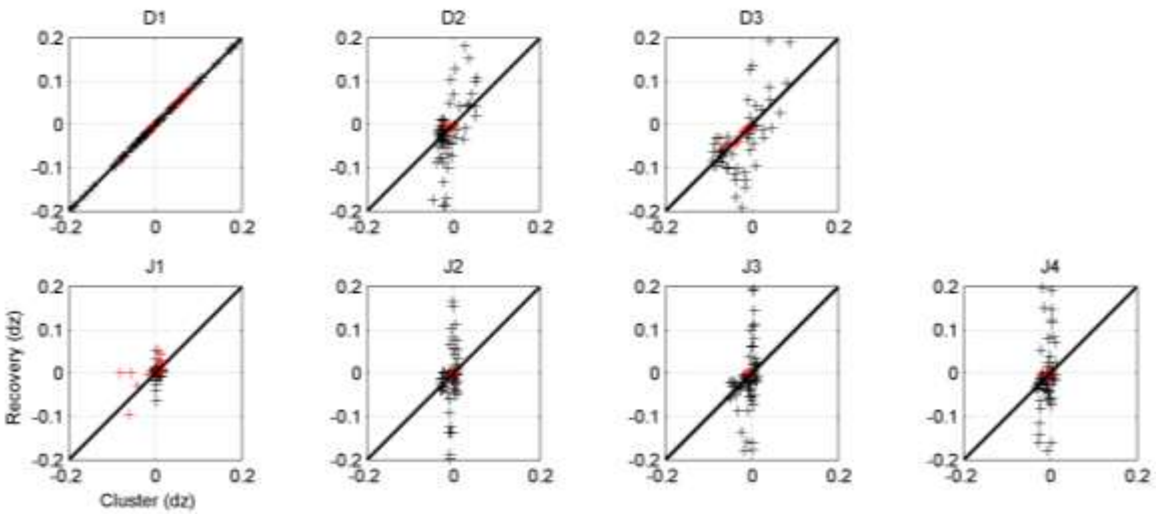

Figure 9 Comparison of bed level change (dz = z_{final}-$z_{initial}$, z:bed level) at each point along the profile within each storm event during the cluster and recovery aplications, negative indicates erosion and positive incates accretion. Black '+' indicates below and red '+' indicates above the threshold dune erosion elevel (3.9 m ODN). For the clarity, -0.2 to 0.2 range is shown.

It should be noted that the D1 storm event has the highest storm power (i.e. erosion potential) while the others have comparatively low values. Morphodynamic response of the profile evolution therefore showed that the impact of D1 event is significantly large compared to the others. It’s occurrence at the start of the cluster will have had a major influence on the profile modifying the impact of every subsequent storm. It is also worth mentioning again, that the recovery resulted in higher bed change due to the interaction of the initial multi-bared pattern. The next section therefore focuses on the dune toe specifically to assess the robustness of the water level threshold in identifying dune erosion events during storm events.

Change in dune toe position

We next compared the change in dune toe elevation during storm events within the cluster and the recovery applications. Dune toe elevation (i.e. interface between beach and dune) of the Sefton beach/dune system is located at around 5 m ODN and varies from summer to winter as the foreshore slope changes (Pye and Blott, 2008). However, at Formby Point, wave erosion at dune toe level occurs when water level exceeds 3.9 m ODN (Parker, 1975). Therefore, we used this level as a proxy above the multi-bared system to compare the storm impacted cross-shore change at the dune toe position. This allows inter-comparing the impacts of all events of the selected storms from low to high severity with the maximum water levels ranging from 2.8 to 5.6 m ODN.

Resulting cross-shore changes at the representative dune toe level are shown in Figure 10 for each storm event. Both cluster and recovery applications show a similar impact, either landward retreat (negative) or seaward advancement due to slumping (positive) of the dune toe level. It is also found that more often the cluster simulations result in a relatively enhanced change in dune toe position compared with that of the recovery simulations. The large change at the dune toe in the cluster is primarily expected due to the interaction of the storms with the nearshore multi-bared system. Once the initial and the most severe event (D1) of the cluster has flattened the multi-bared features, the subsequent storms approach the upper beach and lower dune area with higher wave energy leading to strong morphodynamic change compared with that of the recovery. The largest landward retreat is found during D3 in both applications, while the lowest in the cluster application is during J2 and for the recovery application is during J3. The impact of D3 is likely to be due to the high wave power that is directed directly onshore from the west over two consecutive high waters. Although D1 is more powerful the waves are at a slight angle to the coast and only have one instants of impact during the first high water of the storm period. It is interesting that D3 has most impact for such a low water elevation (max. 3.5 m ODN). The fact the majority of events cause dune erosion even with lower than critical water levels for impact suggests the 3.9 m ODN water threshold could be lower under waves higher than the 2.5 m storm wave threshold (CCO). Only the J1 event (i.e. the lowest severity: 15 m^2hr) indicates slumped material remains, in which the cluster has a higher value. This is mainly due to the fact that J1 had high water levels that were likely to soak the dune under wave action, while the very short (2.5 hour) storm period was unable to erode the slumped dune material following collapse of the dune frontage. In the cluster, the slumping has been enhanced due to the loss of the multi-bared system enabling greater wave impact at the dune toe as a consequence of reduced dissipation across the shoreface. Further description of dune collapsing is referred to Pye and Blott (2008). Particularly, photographs taken from the site (Fig. 6a and b in Pye and Blott, 2008) clearly visualize this mechanism. The event J3 is another event where there is noticeable contrast between the 2 simulations. This storm has a low water level but relatively high waves following 3 events when the wave powers were lower. This event demonstrates how its position in the cluster has caused the systems resilience to be reduced by the initial storms enabling this moderately high powered event to have greater impact on the dunes than if the beach had been fully resilient. This demonstrates how dunes become more vulnerable to high storm waves, even when they occur at water levels below the dune toe location, when the event is positioned later within a cluster of events.

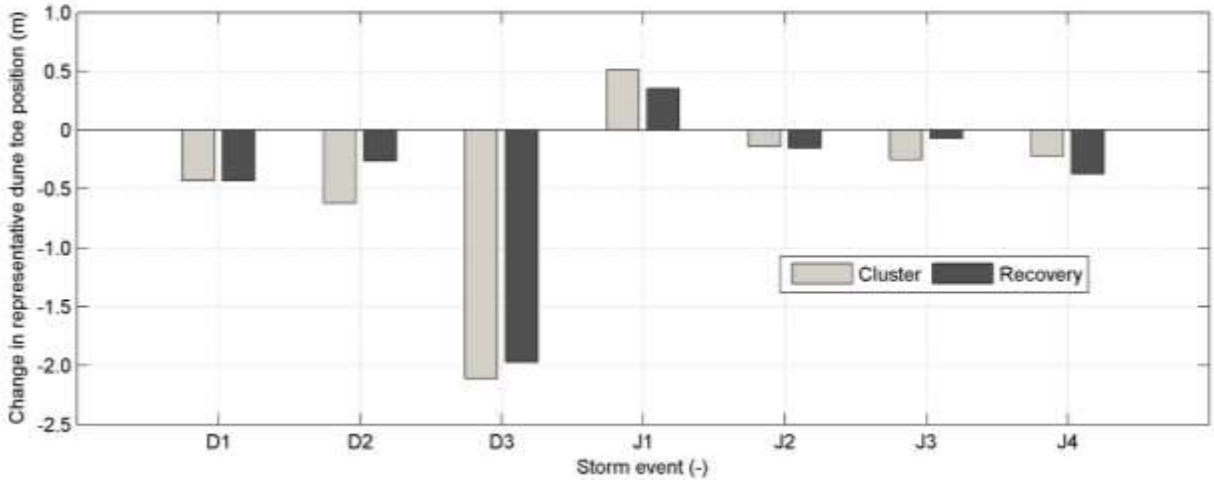

Figure 10 Changes in cross-shore distance of the representative dune toe level (3.9 m) within each storm event in Cluster and Recovery applications (positive/negative values indicate seaward advance/landward retreat)

This analysis indicated that the change in the dune toe position is not necessarily proportional to the storm severity, i.e. high storm power results large changes and vice versa. Further, relatively weak storm can induce a large change at the dune toe level and this impact is further increased if the storm occurs within a storm cluster. However, for such storms the multi-bared system can remain relatively unaffected under the low water action. Due to the nearshore multi-bared features at Formby Point, the storm clustering effect modifies the erosion/accretion along the cross-shore profile. Within a cluster the resilience of the system changes compared with that of the fully recovered system, causing the dunes to become typically more vulnerable to storm impacts during high powered events.

6. Conclusions

Impacts of storm clustering during the winter 2013/2014 on the Formby Point (Sefton coast, UK) beach/dune system were investigated using a numerical model. The modelling approach used the XBeach coastal area model in 1D mode to simulate the cross-shore profile evolution at Formby Point: the most dynamic area of the Sefton coast. Offshore tide and wave boundary forcings were imposed using the measured data during the storms. The model was first calibrated against the measured post-storm profile and then use to simulate clustering effects (i.e. using the post-storm profile in the previous event as the pre-storm profile for the subsequent) and isolated impact on a recovered system (i.e. using the same pre-storm profile for all events). Predicted evolution was analysed to enhance the understanding of the storm clustering effect using Formby Point as a case study. The following conclusions are drawn:

- Compared with many coastal locations, the Sefton coast has a rich set of information on tides, waves and morphological changes. The recent storms combined with improved coastal monitoring schemes at Sefton have enabled detailed analysis of storm clustering effects on the Formby Point morphodynamics.
- It was found that the first storm event during December 2013 – January 2014 period can be regarded as exceptionally severe ($H_{s,max}$ = 5.0 m and WL = 5.6 m ODN) due to occurrence at spring-high tide. Seven successive storms at very close intervals occurred during this period, which is unique.
- Analysis of the severity of individual storms in the cluster using ‘storm power’ showed that the lowest severity storm in December 2013 is more severe than the highest severity event in January 2014.
- Storm impact across the beach/dune system for the isolated storms on the full recovery profile is higher compared with the impact of that event within the cluster.

However, the initial storms in the latter always interact with the initial multi-bared system leading strong erosion and accretion which reduces the resilience of the system typically making the dunes more vulnerable to erosion from proceeding large wave events.

- For the typical background winter storm wave conditions, the suggested 3.9 m ODN threshold for dune erosion (Parker, 1975) is considered accurate. This threshold is found to define a condition when water levels enable noticeable dune erosion events due to moderate waves, while the rest of the beach profile remains relatively unaffected. Under these conditions the slumped material is more likely to remain on the beach face providing a potential sediment source for dune recovery. However, all of the events have an impact on the upper beach-dune interface (defined as 3.9 m ODN), even when the maximum water level is up to about1 m lower than the threshold for dune erosion. The suggested 3.9 m ODN (Parker, 1975) threshold for dune erosion is too high for extreme wave events that noticeably exceed the Liverpool Bay storm wave threshold (2.5 m, CCO).
- After 3 large events the impact of clustering starts to prevent noticeable evolution of the beach/dune system, after 4 events any further evolution is very small. However when concentrating on the position of the dune toe, the cluster of events can still enhance the local impact on the dune frontage.
- The impact on the dune toe seems to also depend on how many high waters within the storm event high wave conditions occur for.

Results of the present model study provide preliminary insights into the storm clustering effects on morphodynamics at Formby Point due to wave impact. These findings will have important implications on interpretation of the observed dune erosion and will be useful in formulating sustainable dune management strategies. Further research is required to explore the range of water levels that enable waves of variable size to impact the dune frontage, and also, the range in water levels that cause dune soaking causing erosion even in low or no wave conditions. We suggest that Parker's (1975) lower water level threshold is appropriate for storm waves to cause erosive impact, but a higher water level, as suggested by Plater et al. (2010), just above the mean high water spring tide is required to enhance or cause erosion due to dune soaking. The outcome of this research will form the foundation to move away from the traditional 'return period' approach used to determine coastal damage in which erosion levels can be significantly underestimated.

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